Detector Needs for Direct Spectroscopic Biosignature Characterization

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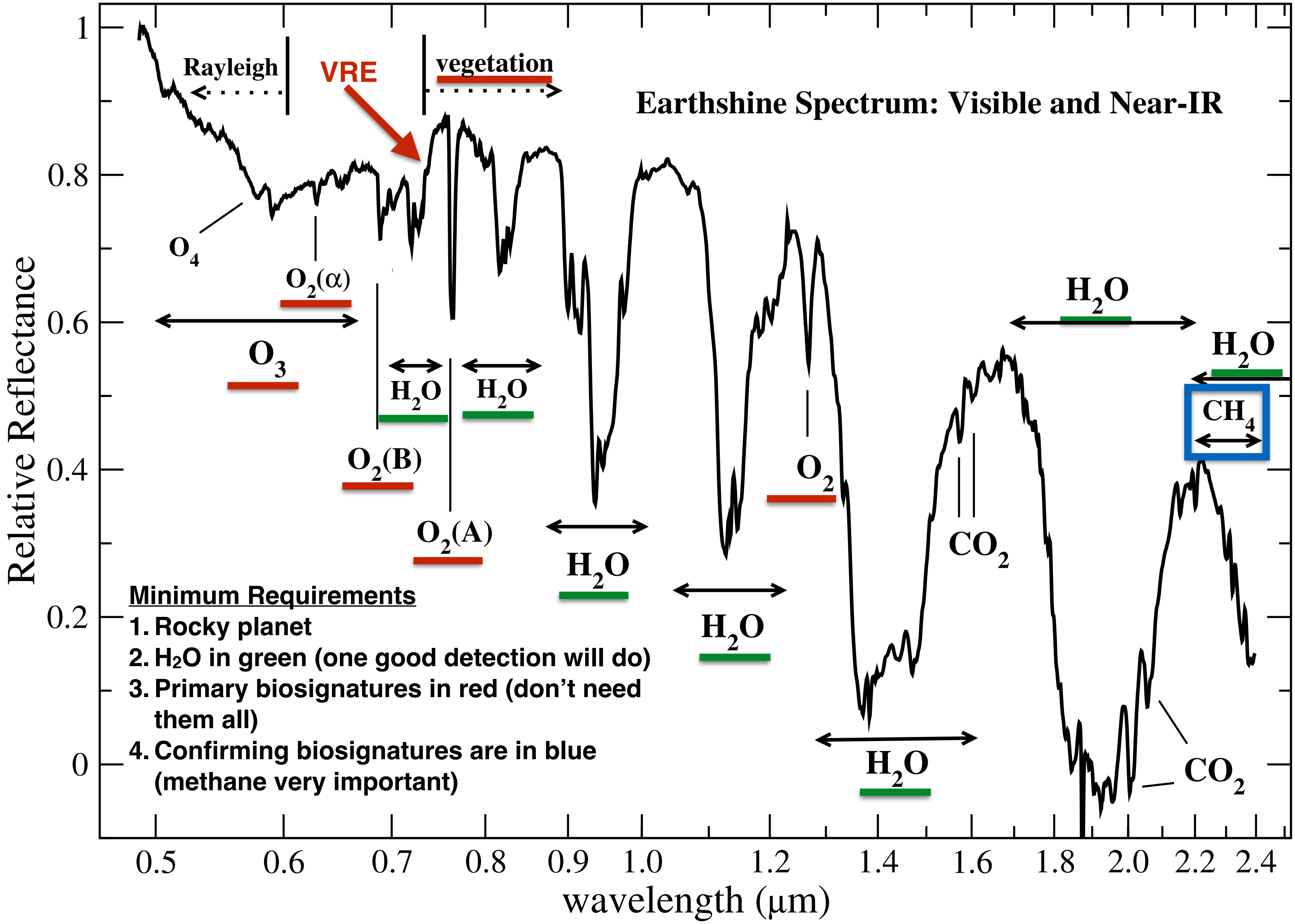
Presented at SPIE Optics + Photonics
UV/Optical/IR Space Telescopes and Instruments: Innovative Technologies and Concepts VII
Paper 9602-12
9 August 2015, San Diego, CA   USA

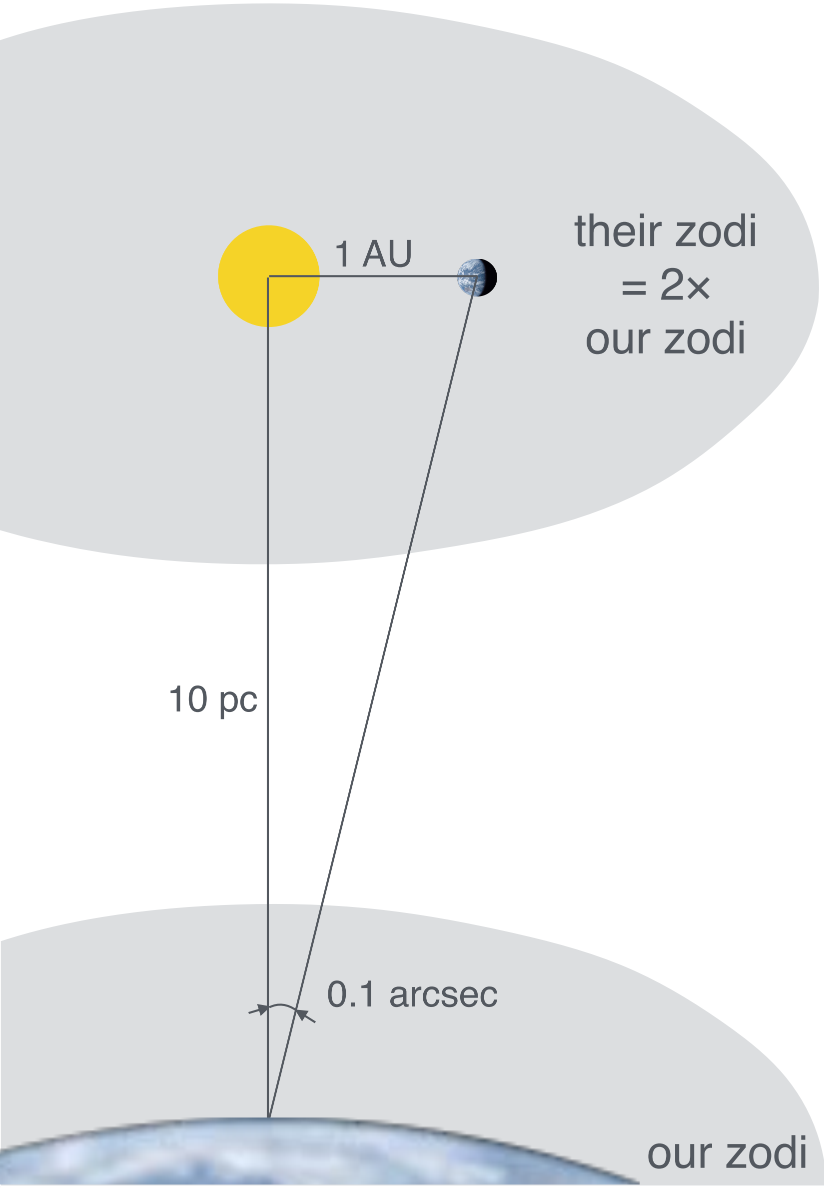
Biosignatures in the Visible and Near-IR



Green = Necessary for life; Red = Biosignature; Blue = Helps to rule out false positives

Spectrum from Turnbull et al. 2006, ApJ, 644, 551

A Single Photon Detector[1] (SPD) is Clearly Preferred for Spectroscopic Biosignature Characterization

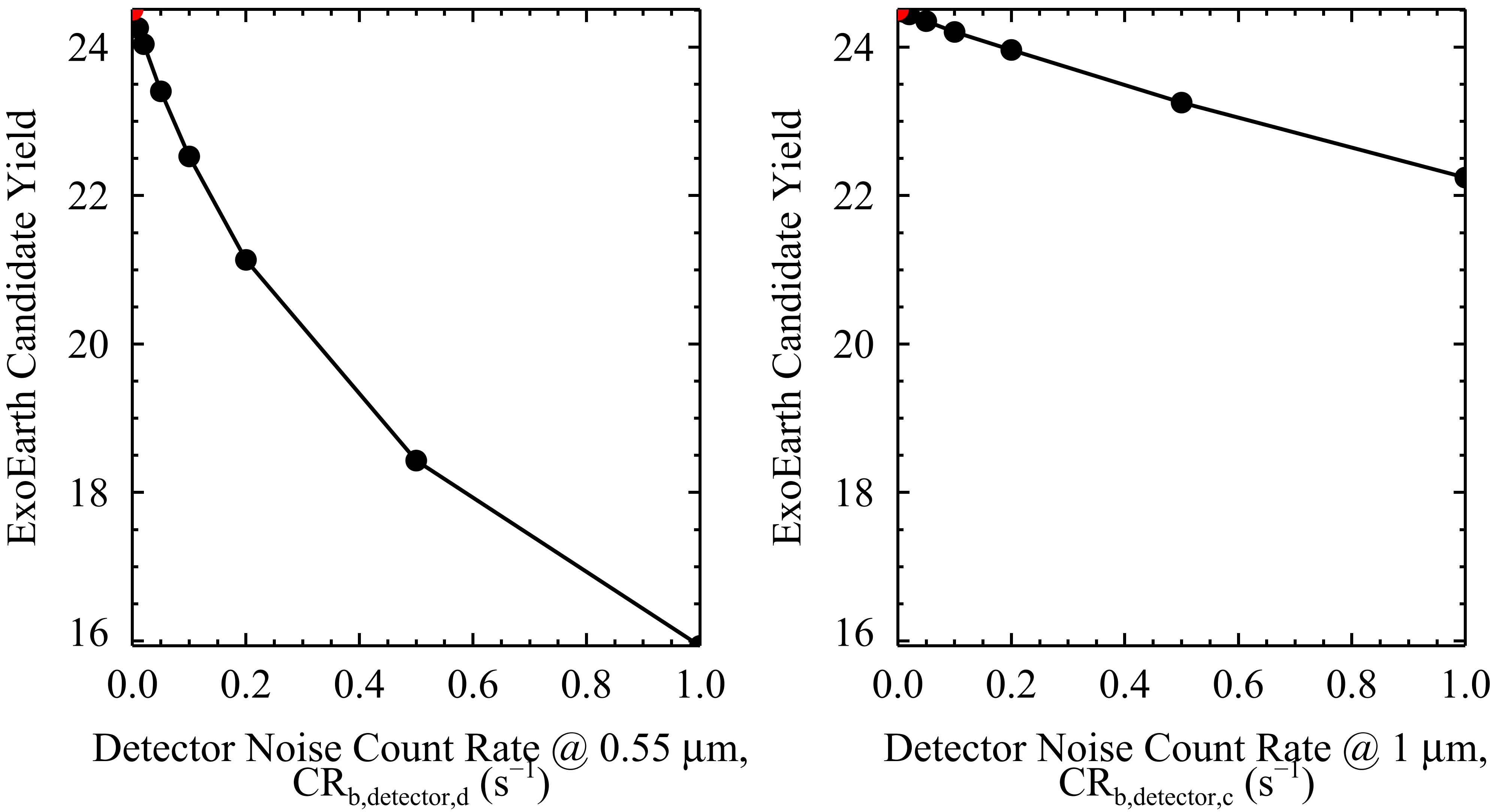


Earth Twin at 10 pc

- Toy model assumes a perfect coronagraph
- Assumptions
  - 25 % efficient IFU spectrograph
  - pixel size = $0.7 \times 1.22 \dfrac{\lambda_{crit}}{D}$
  - λ = 550 nm
  - $R = \dfrac{\lambda}{\Delta\lambda} = 150$
  - Background = 3 × zodi
- Background flux is (very roughly) $\lesssim$ 0.001 cnt/s/pix!
- Realistic scattered light increases background somewhat, *but we want detectors that can take advantage of the best coronagraph or starshade that we can get!*
- **An SPD is clearly preferred**
- More realistic models reach the same conclusion, a SPD is clearly preferred to maximize ExoEarth yields using a coronagraph and IFU spectrograph (Stark, Roberge, & Mandell, *et al.* 2015, ApJ, 808, 149)

[1] Better than photon counting, an SPD counts individual photons without adding appreciable noise from any other source

How Detector Noise Affects ExoEarth Yield



Credit: Stark, Roberge, & Mandell, et al. 2015, ApJ, 808, 149

ATLAST's Detector "Technology Gap" Analysis

Technology Component	Parameter	Required	State-of-the-Art	Current TRL	Technology, Engineering, Manufacturing Gap
Vis-NIR Single Photon Detectors for Enabling Exoplanet Science	Operational Bandwidth	400 nm – 1.8 µm (2.5 µm goal)	EMCCD technology is promising, but require radiation hardness testing, and have a hard cutoff at 1.1 µm; HgCdTe APDs are candidates for NIR but need improvements in dark counts rates; Superconducting MKID and TES detectors meet requirements, but need cryogenic temperatures	3 – 5	Technology, Engineering, Manufacturing
	Read Noise	<< 1 e^-			
	Dark Current	< 0.001 e^-/pix/s			
	Spurious Count Rate	Small compared to integrated dark current			
	Quantum Efficiency	> 80% over entire band			
	Format	> 2k × 2k pixels			
	Other	Radiation hard, minimum 5-year lifetime at SEL2, Non-cryogenic operation preferable			
UV Single Photon Detectors for Enhanced Exoplanet Science	Operational Bandwidth	200 nm – 400 nm	GaN-based EBCMOS and MCP detectors meet required noise specifications, but require improvements in quantum efficiency to > 50% and improvements in lifetime Superconducting MKID and TES detectors also apply here	2 – 4	Technology, Engineering, Manufacturing
	Read Noise	<< 1 e^-			
	Dark Current	< 0.001 e^-/pix/s			
	Spurious Count Rate	Small compared to integrated dark current			
	Quantum Efficiency	> 50% over the entire band			
	Format	> 2k × 2k pixels			
	Other	Radiation hard, minimum 5-year lifetime at SEL2, Non-cryogenic operation preferable			
Large-format High-Sensitivity UV Detectors for General Astrophysics	Operational Bandwidth	90 nm – 300 nm	Same as above δ-doped EMCCD also a candidate here, but requires improved radiation hardness and reduction in clock-induced charge	4	Engineering, Manufacturing
	Read Noise	< 5 e^-			
	Quantum Efficiency	> 70%			
	Format	> 2k × 2k pixels			
	Other	Radiation hard, minimum lifetime at SEL2, Non-cryogenic operation preferable, Visible blind			

MKID and TES detectos are energy resolving. For these, the required spectral resolution is R > 70 with a goal of R > 150

From Bolcar, M.R. 2015, "Technology Development for the Advanced Technology Large Aperture Space Telescope (ATLAST) as a Candidate Large UV-Optical-Infrared (LUVOIR) Surveyor", Proc SPIE (this conference), Paper 9602-8

Candidate Detector Technologies for ExoEarth Identification and Characterization

Technology	Far UV 90 (TBC) — 200 nm Imaging	Far UV Spec.	Near-UV 200 — 350 nm Imaging	Near-UV Spec.	Visible 350 — 950 nm Imaging	Visible Spec.	Visible WFSG[1]	Visible Speckle Nulling	Near-IR 950 nm — 5 μm Imaging	Near-IR Spec.	Mid-IR 5 μm — 8 μm (TBC) Imaging	Mid-IR Spec.
Electron-bombarded CMOS	Testing needed	Testing needed										
Microchannel Plate Detectors	Brightness limits; Low QE; Finite Lifetime	Brightness limits; Low QE; Finite Lifetime										
CCD (δ-doped)			Rad. hardness									
CMOS (δ-doped)												
EMCCD (δ-doped)		Rad. hardness	Rad. hardness	Rad. hardness								
p-channel CCD (δ-doped)												
Si PIN Hybrid (δ-doped)												
Wide Bandgap Hybrid	TRL < 4	TRL < 4	TRL < 4	TRL < 4								
CCD					Rad. hardness		Rad. hardness					
CMOS					Testing needed		Testing needed					
EMCCD					Rad. hardness	Rad. hardness	Rad. hardness	Rad. hardness				
p-channel CCD					TRL ≥ 6		TRL ≥ 6					
Si PIN Hybrid					TRL ≥ 6		TRL ≥ 6					
HgCdTe Hybrid					TRL ≥ 6		TRL ≥ 6		TRL ≥ 6			
HgCdTe APD Hybrid					Reduce dark current	Reduce dark current	Testing needed	Testing needed	Reduce dark current	Reduce dark current		
HgCdTe Hybrid												
MKID array	TRL < 5	TRL < 5	TRL < 5	TRL < 5	TRL < 5	TRL < 5	TRL < 5	TRL < 5	TRL < 5	TRL < 5	TRL < 5	TRL < 5
TES array	TRL < 5	TRL < 5	TRL < 5	TRL < 5	TRL < 5	TRL < 5	TRL < 5	TRL < 5	TRL < 5	TRL < 5	TRL < 5	TRL < 5
SNSPD	Reduce dark current	Reduce dark current	Reduce dark current	Reduce dark current	Reduce dark current	Reduce dark current	Reduce dark current	Reduce dark current	Reduce dark current	Reduce dark current	Reduce dark current	Reduce dark current
Si:As Hybrid											TRL ≥ 6	

[1] Wavefront sensing/guiding

TRL ≥ 6; Sufficiently mature for pre Phase-A
Promising technology, more work needed in specific areas
Promising technology
Cryocooler required

- Imaging used for candidate identification
- Spectroscopy used for biosignature characterization
- This table is a work in progress, additions welcome if NASA TRL ≥ 3, corrections welcome

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For Spectroscopic Characterization, more Detector Candidates would be Good

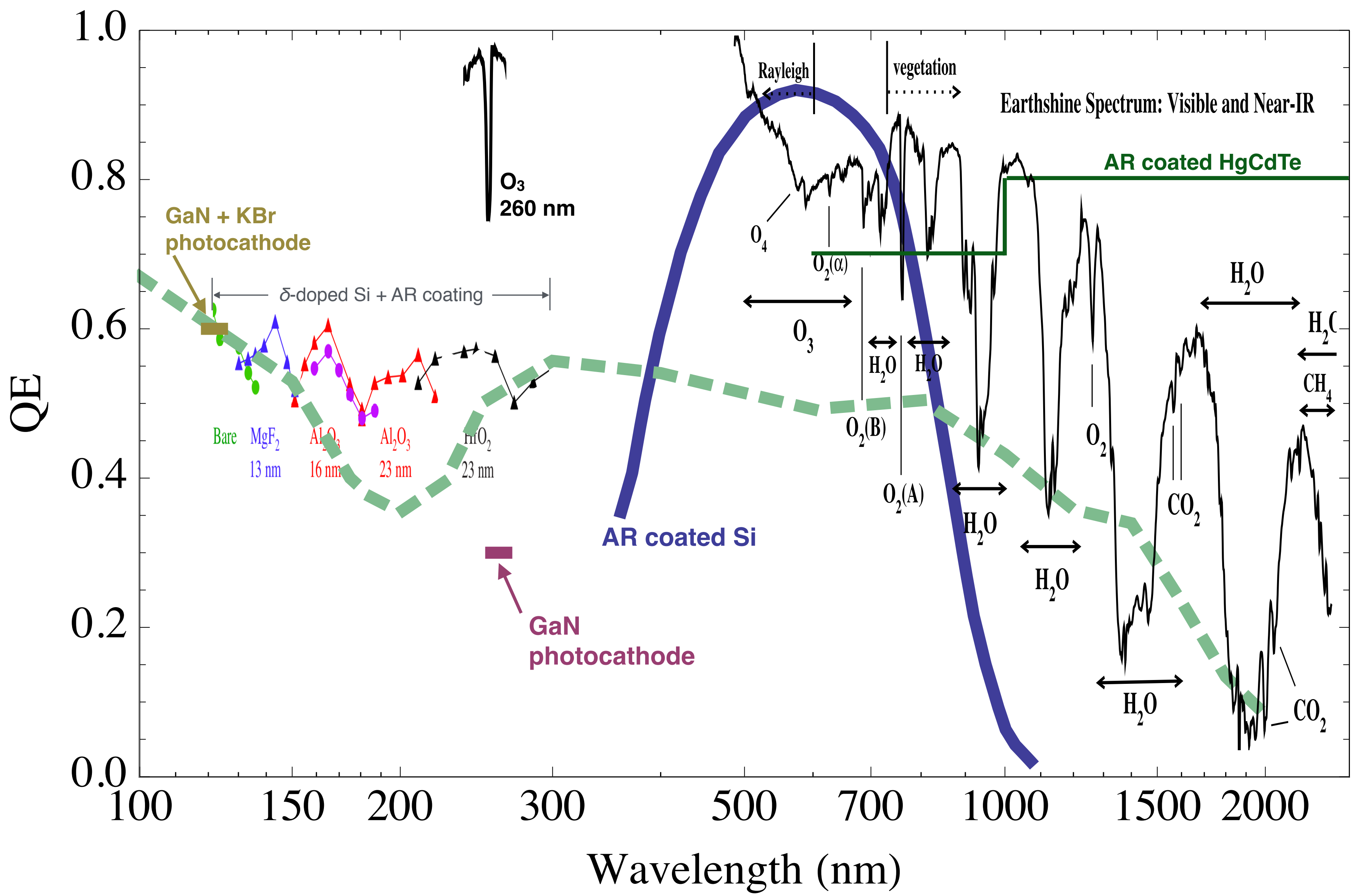
Technology	Visible 350 — 950 nm	Near-IR 950 nm — 5 µm	Mid-IR 5 µm — 8 µm
CCD	Rad. hardness		
CMOS			
EMCCD	Rad. hardness		
p-channel CCD			
Si PIN Hybrid			
HgCdTe Hybrid			
HgCdTe APD Hybrid	Reduce dark current	Reduce dark current	
MKID array	TRL < 5	TRL < 5	TRL < 5
TES array	TRL < 5	TRL < 5	TRL < 5
SNSPD	Reduce dark current	Reduce dark current	Reduce dark current
Si:As Hybrid			

Cryogenic detectors

(green)	TRL ≥ 6; Sufficiently mature for pre Phase-A
(blue)	Promising technology, more work needed in specific areas
(light blue)	Promising technology
(grey)	Cryocooler required
(yellow)	May be worth looking into with additional optimization

- Non-cryogenic detectors are strongly preferred by coronagraph optics experts if they can meet performance requirements
- Yellow indicates that I am not aware of any fundamental reason why the read noise could not be further reduced with targeted development

Achieved & Proposed QE vs. Wavelength and Life Signatures



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Electron Multiplying CCD (EMCCD)

Other EMCCD Talks at this Conference Include…

Fireball-2: a UV multi-object spectrograph for detecting the low z circumgalactic medium

David Schiminovich, Erika T. Hamden, D. Christopher Martin, Bruno Milliard, Robert Grange, Shouleh Nikzad, Lauren Corlies, Robert Crabill, Didier Ferrand, Albert Gomes, Anne-Sophie Hutter, Marc Jaquet, April Jewell, Gillian Kyne, Vincent Lamande, Gerard Lemaitre, Michele Limon, Nicole Lingner, Marc Llored, Mateusz Matuszewski, Pierre Mege, Frederi Mirc, Patrick Morrissey, Hwei Ru Ong, Alain Origne, Sandrine Pascal, Celine Peroux, Samuel Quiret, Didier Vibert, Jose M. Zorrilla

10 August 2015 • 8:20 - 8:40 AM I Part of SPIE Optical Engineering + Applications

Detector performance for the FIREBall-2 UV experiment

April D. Jewell, Erika T. Hamden, Hwei Ru Ong, John Hennessy, Timothy Goodsall, Charles Shapiro, Samuel R. Cheng, Todd J. Jones, Alexander G. Carver, Michael E. Hoenk, David Schiminovich, D. C. Martin, Shouleh Nikzad

10 August 2015 • 8:40 - 9:00 AM I Part of SPIE Optical Engineering + Applications

Noise and dark performance for FIREBall-2 EMCCD delta-doped CCD detector

Erika T. Hamden, Nicole Lingner, Gillian Kyne, Patrick Morrissey, D. Christopher Martin

10 August 2015 • 9:00 - 9:20 AM I Part of SPIE Optical Engineering + Applications

Requirements and design reference mission for the WFIRST-AFTA coronagraph instrument

Richard Demers, Frank G. Dekens, Robert J. Calvet, Zensheu Chang, Robert T. Effinger, Eric M. Ek, Laura Jones, Anthony Loc, Bijan Nemati, Martin Charley Noecker, Timothy Neville, Hung Pham, Hong Tang, Juan Villalvazo

11 August 2015 • 8:00 - 8:20 AM I Part of SPIE Optical Engineering + Applications

The impact of radiation damage on photon counting with an EM-CCD for the WFIRST-AFTA coronagraph

Nathan L. Bush, David J. Hall, Andrew D. Holland, Ross Burgon, Neil J. Murray, Jason P. D. Gow, Matthew R. Soman, Doug Jordan, Richard Demers, Leon K. Harding, Michael E. Hoenk, Darren Michaels, Bijan Nemati, Pavani Peddada

11 August 2015 • 2:10 - 2:30 PM I Part of SPIE Optical Engineering + Applications

Electron multiplication CCD detector technology advancement for the WFIRST-AFTA coronagraph integral field spectrograph

Leon K. Harding, Michael Cherng, Richard Demers, Michael E. Hoenk, Darren Michaels, Bijan Nemati, Pavani Peddada

11 August 2015 • 2:30 - 2:50 PM I Part of SPIE Optical Engineering + Applications

Maturing CCD photon counting technology for space flight

Udayan Mallik, Richard G. Lyon, Michael McElwain, Dominic J. Benford, Mark Clampin, Brian A. HIcks

12 August 2015 • 4:10 - 4:30 PM I Part of SPIE Optical Engineering + Applications

Electron Multiplying CCDs (EMCCD) for Visible

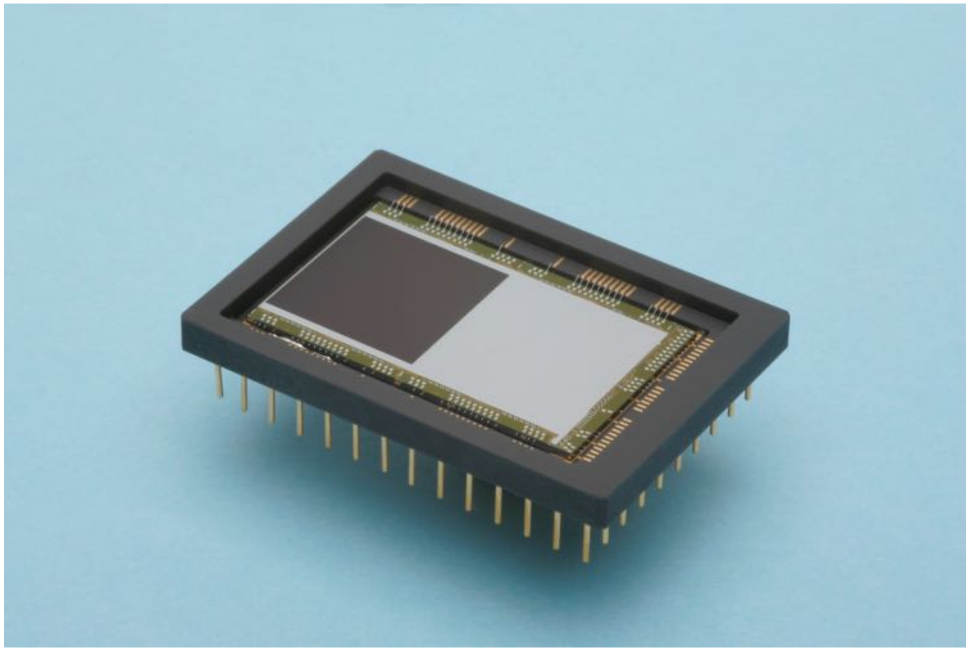
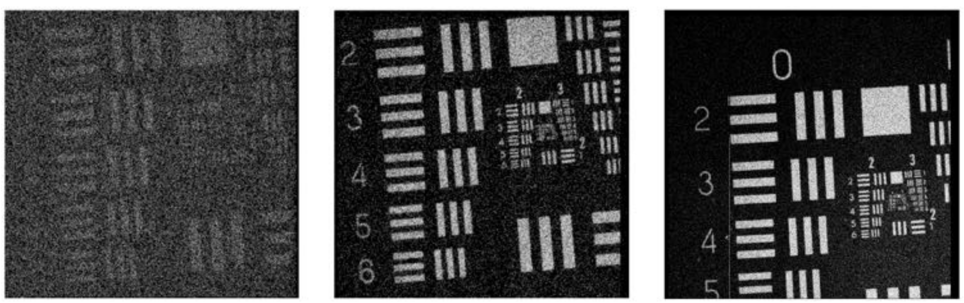


Fig. Credit: e2v CCD201



Conventional CCD | Intensified Imager | Photon Counting

Fig. Credit: Wen, Y., Rauscher, B. J., Baker, R. G., et al. 2006, Proc SPIE, 6276, 44

- Uses impact ionization by electrons to function like a solid state image intensifier
- Basic principles first documented in 1992 by Hynceck of Texas Instruments[1]
- Subsequently patented by e2v in Europe[2] and Hynceck in U.S.[3]
- Can be used as: (1) conventional CCD, (2) intensified CCD, and (3) photon counting Geiger CCD
- Baselined for use in the WFIRST coronagraph

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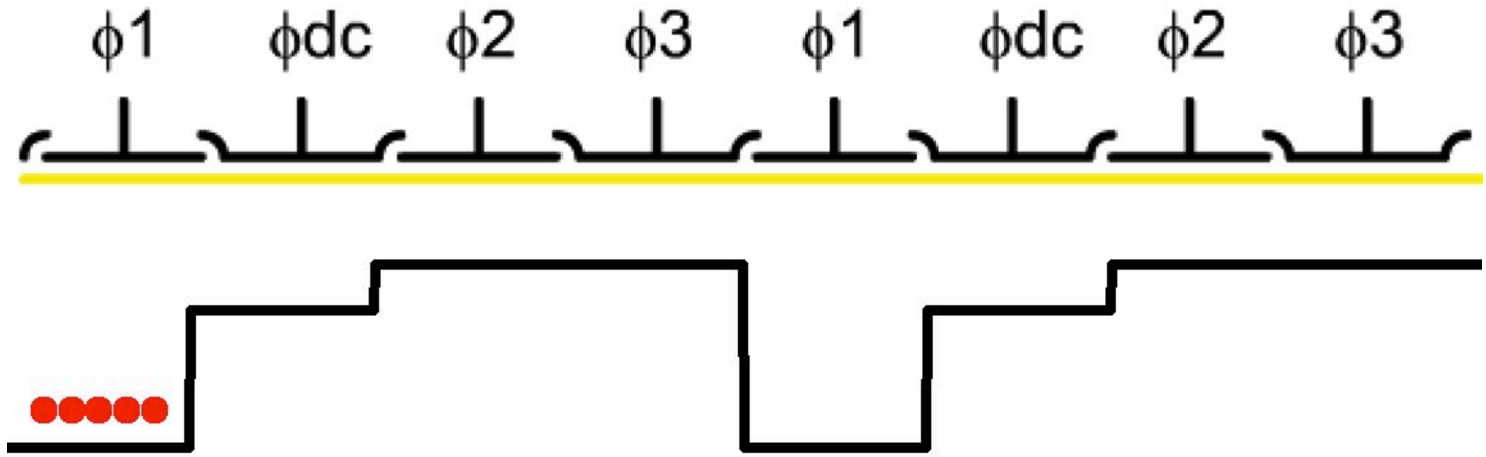
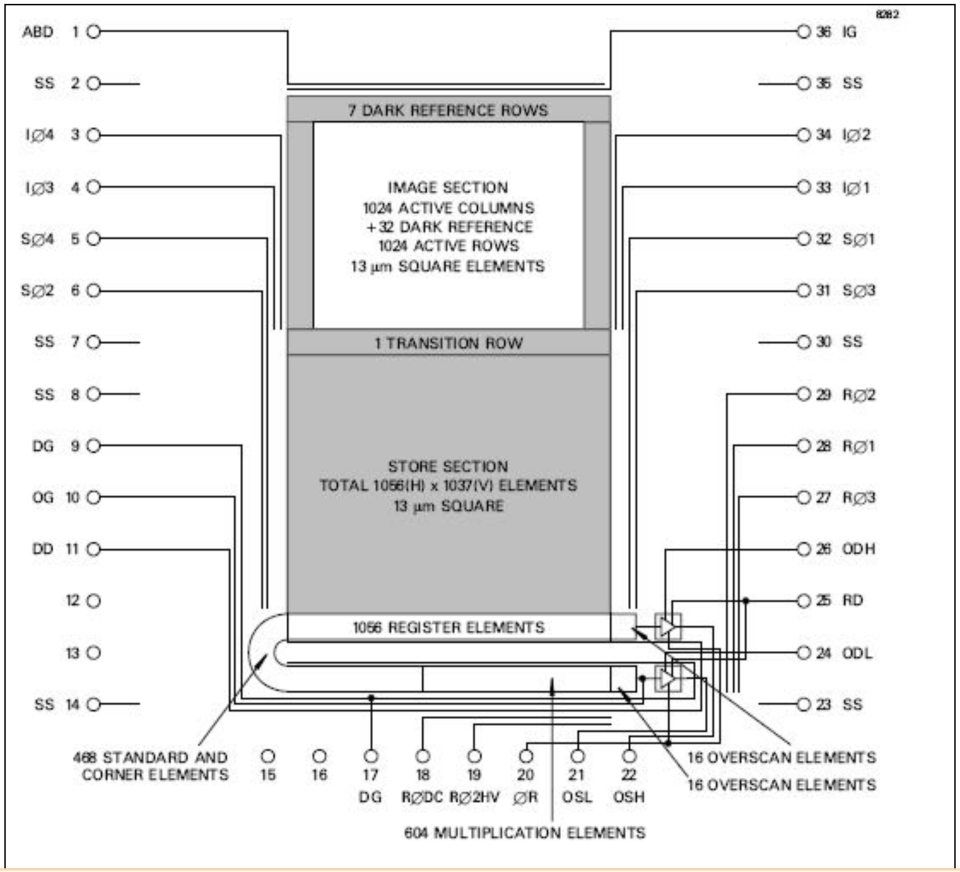
[1] Hynecek, J. 1992, IEEE Transactions on Electron Devices, 39, 1972
[2] Burt, D.J. and Bell, R.T. 1998, European Patent Office, Patent EP 0 866 501 A1
[3] Hynecek, J. 2001, U.S. Patent Office, Patent US 6,278,142 B1

EMCCD Operating Principle



EMCCD Architecture



Example of avalanche-gain architecture (e2v CCD65)

•Scientific CCDs normally have readout noise floors of 2-5 e- rms.

•Avalanche gain technology (electron multiplication) allows sub-electron read-noise.

•**Several important considerations:**

•Cooling to suppress dark current becomes very important

•Good control of operating temperature and HV-clock level are important for gain stability

•Noise statistics are non-Gaussian resulting from the stochastic gain process

•Clock-induced charge ~~can~~ becomes significant at sub-electron signal levels

L3Vision

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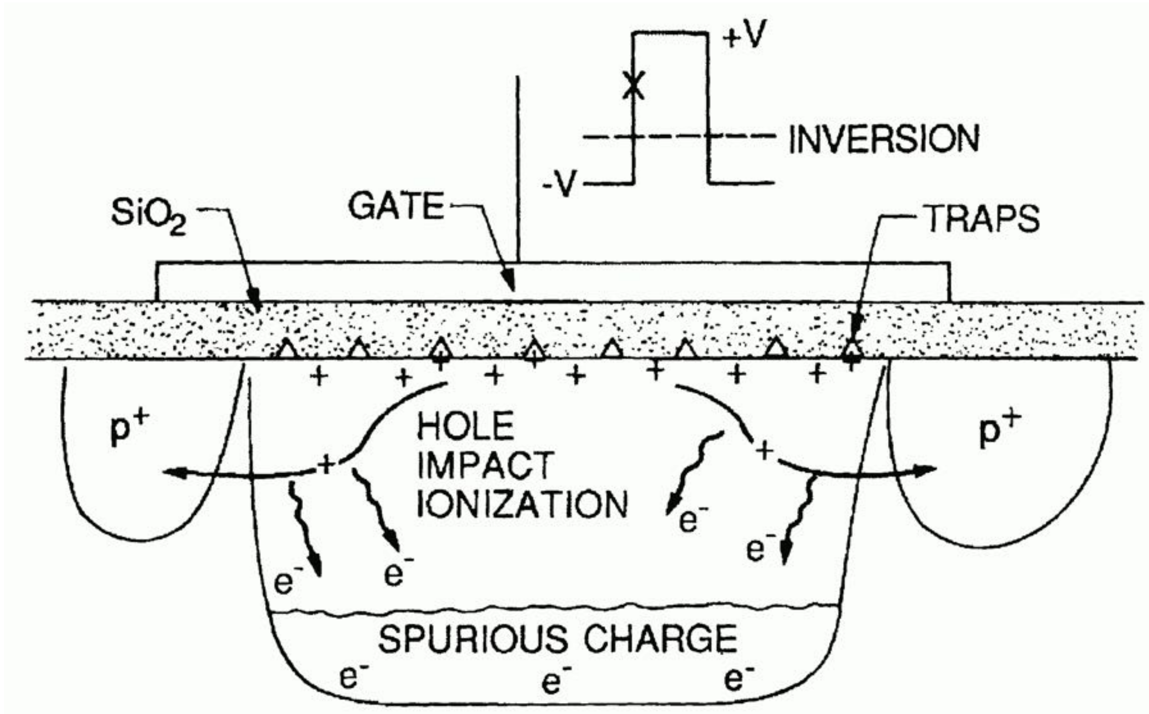
Performance Issues

- Arguably most significant is clock induced charge (CIC)
  - CIC occurs in any CCD, but is ordinarily buried in read noise —becomes obvious when trying to detect individual photons
  - State-of-art current ~0.002 cts/pix/frame
- Janesick attributes CIC to impact ionization when holes are released from traps in the interface between the Si and SiO_2
- CIC arises when the clock phase comes out of inversion and stuck holes are released a short time later when they see a voltage large enough to cause impact ionization
- Largely eliminated when CCD is not run in inversion, but dark current goes up
- Can be mitigated by shaping clocks



Credit: Janesick, J. 2001, *Scientific charge-coupled devices*, SPIE Press

EMCCDs: Where Work is Needed for ATLAST

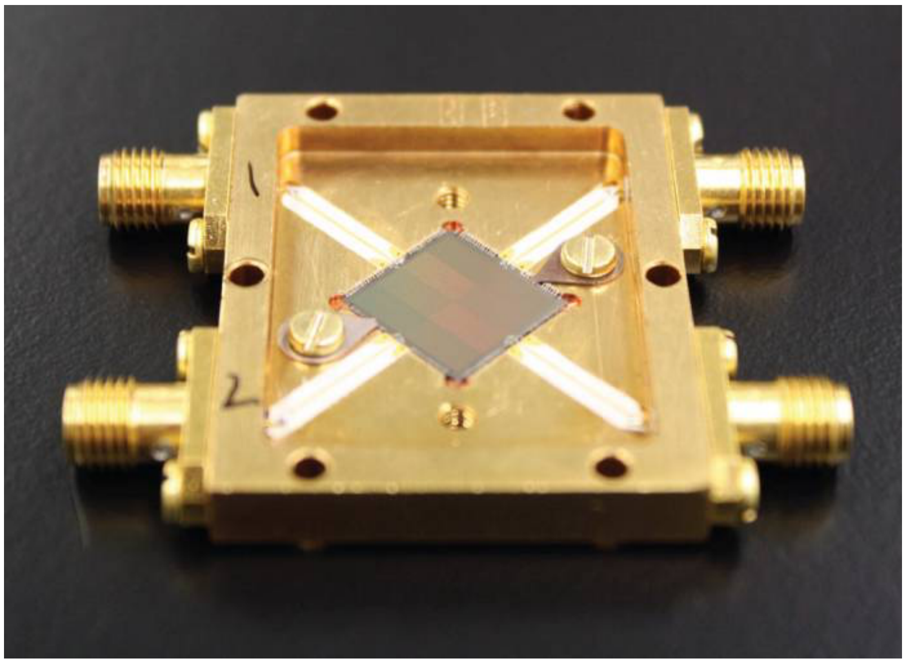
- *New* EMCCDs arguably meet performance requirements for spectroscopic biosignature characterization
- However, they will degrade in the space radiation environment (as would any conventional CCD)
- JPL is conducting a radiation test now for WFIRST, but performance requirements for ATLAST will be more challenging
- Design enhancements to increase radiation tolerance beneficial
- Further reduction in clock induced charge beneficial
- Improving the red QE beneficial

Microwave Kinetic Inductance Device (MKID)

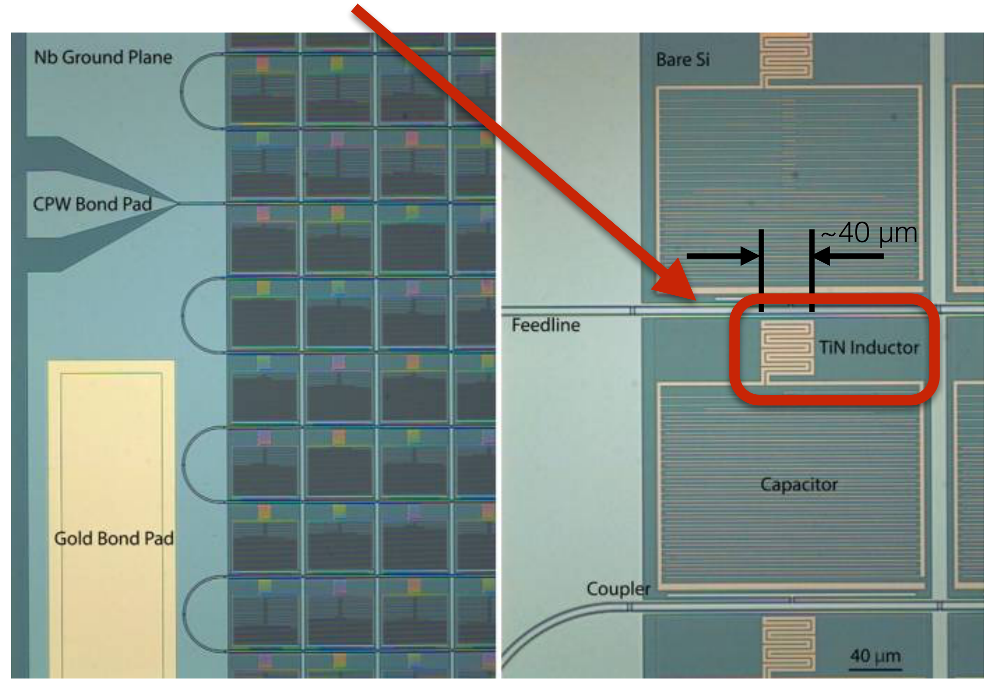
MKIDs for the Visible and near-IR

An MKID array was used for UVOIR astronomy at the Palomar 5-m (Mazin et al. 2013, PASP, 125, 1348)

Incident photons detected in inductor



A 2024 pixel UVOIR MKID array with microlens array removed



Left) Microscope image of a 2024 pixel MKID array used at the Palomar 5-m telescope. Right) Zoomed in view.

Fig. Credit: Mazin, B. A., Meeker, S. R., Strader, M. J., et al. 2013, PASP, 125, 1348–1361

MKID Operating Principle

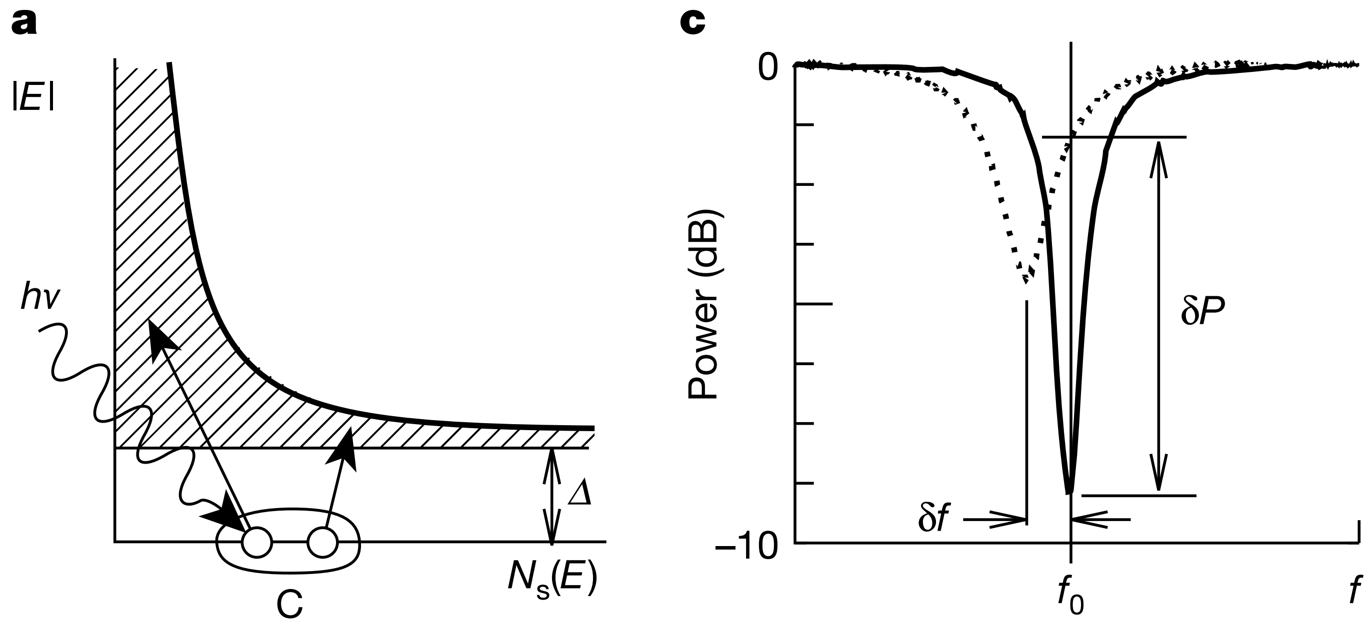
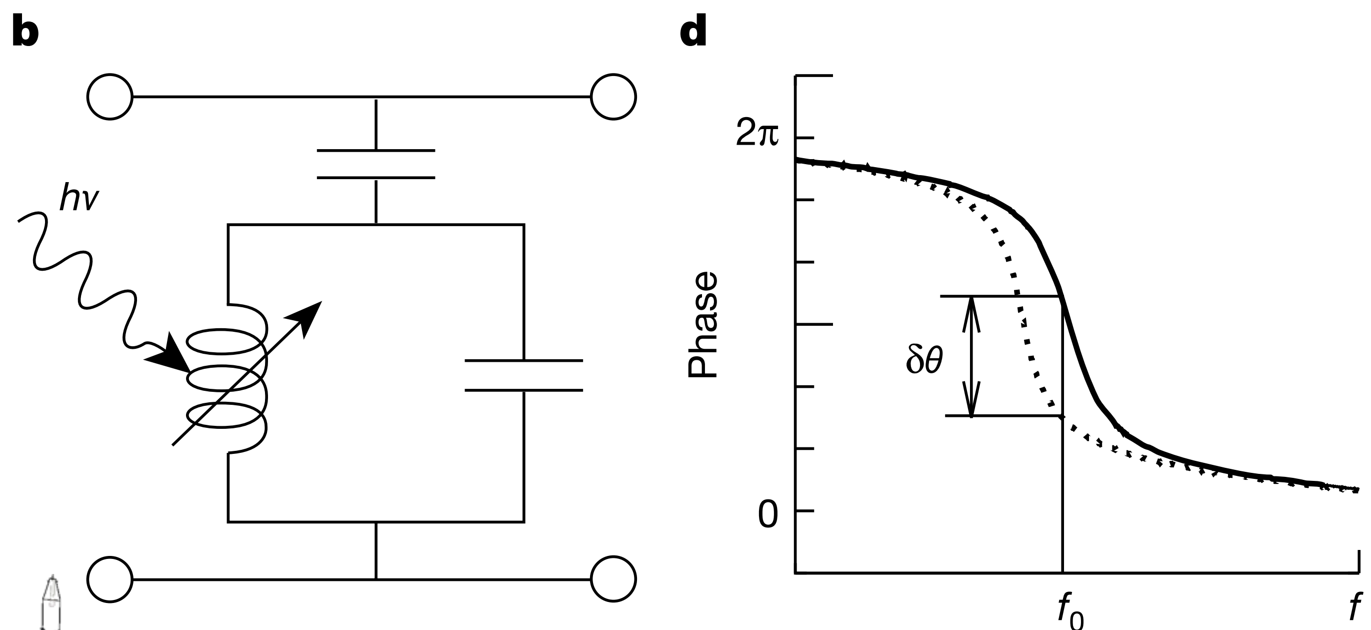


Fig. Credit: Day, P. K., LeDuc, H. G., Mazin, B. A., Vayonakis, A. & Zmuidzinas, J. 2003, Nature, 425, 817–821



a) Photons with energy hν > 2Δ are absorbed in a superconducting film breaking Cooper pairs and creating quasiparticles

b) The increase in quasiparticle density changes the (mainly inductive) surface impedance, $Z_s=R_s+i\omega L_s$ of the film which is used as part of a microwave resonant circuit that is capacitively coupled to a multiplexing through line.

c) On resonance, the LC circuit loads the through line, producing a dip in its transmission. This moves the resonance to lower frequency (due to L_s), and makes the dip broader and shallower (due to R_s). Both of these effects contribute to changing the amplitude and q

d) phase of a microwave probe signal transmitted though the circuit.

MKIDs: Where Work is Needed

- Higher energy resolving power is required for spectroscopic biosignature characterization
  - median(R) ~ 8 at 400 nm is documented[1]
  - **<u>R > 70 required</u>**
  - R > 150 goal
- Larger arrays are needed
  - 2024 pixels documented[1]
  - ~ 100 x 100 arrays required
  - We understand that work on larger arrays is already in progress
- More information on the achieved detection efficiency is needed
  - Published values suggest that the detection efficiency of the ARCONS MKIDs +μ-lens+Electronics may be < 30% at 1 μm[1]
  - > 35% required for ~700 nm < λ < 2.5 μm

[1] *Mazin, B. A., Meeker, S. R., Strader, M. J., et al. 2013, Publications of the Astronomical Society of the Pacific, 125, 1348–1361*

Summary

- The search for life on exoplanets using spectroscopic biosignatures is real —expected to be an important topic in the next Decadal Survey and NASA missions are already being planned

- Significant technical challenges include precision large-scale optics, ultra-stable structures, starlight suppression, ***and detectors***

- Good candidate detectors exist, but all need work before they will be ready

- One important distinction is that between conventional semiconductor detectors and superconducting single photon detectors

  - Semiconductor detectors require a spectrograph and run warm. But, no semiconductor detector has simultaneously met read noise and dark current requirements for spectroscopic biosignature characterization after radiation exposure

  - Superconducting detectors including MKIDs and TESs run at $T < 1$ K, but have already met read noise and dark current requirements. More work needed to deliver required built in spectral resolution and acceptable QE

- These challenges are real, but solvable, with appropriate strategic investment and development

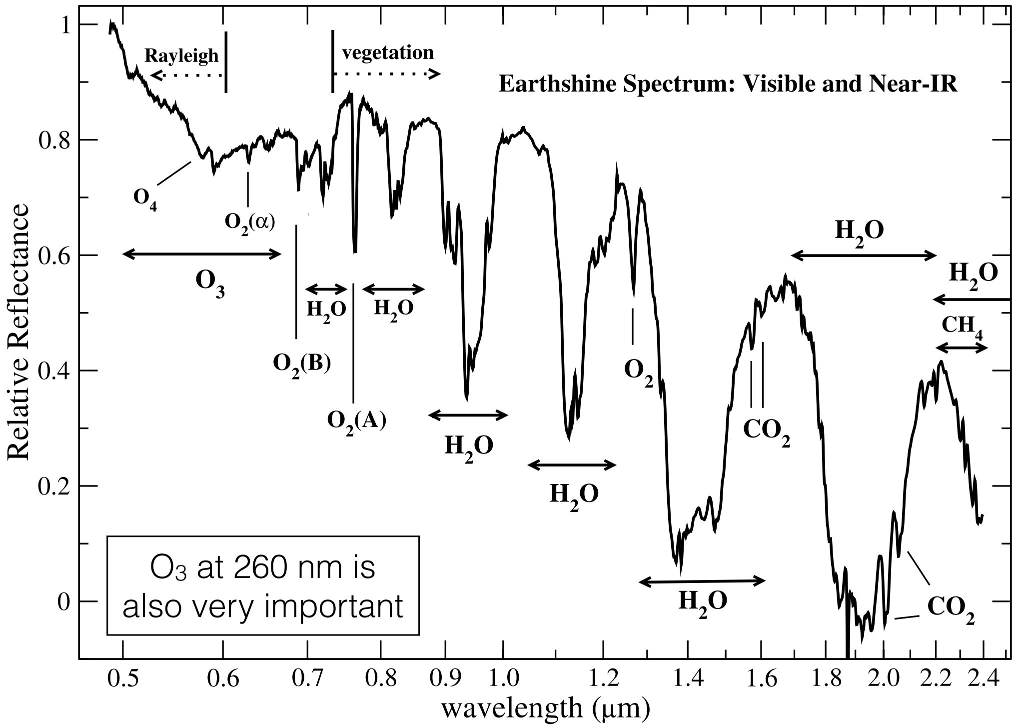
Backup Charts

What is,
"Direct Spectroscopic Biosignature Characterization"?

- **Direct** = imaging the exoplanet itself
  - Contrasts with transit technique that measures the effect of an exoplanet on light from its host star
  - Uses a coronagraph or starshade to suppress light from the host star
- **Spectroscopic** = low resolution ($R = \lambda / \Delta\lambda \sim 100$) imaging spectroscopy to measure atmospheric features in the exoplanet
- **Biosignature** = aim is to characterize molecular and other atmospheric features that are thought to indicate biological processes

Biosignatures: Spectroscopic Signs of Life

Earth seen as an exoplanet



Earthshine spectrum from Turnbull et al. 2006, ApJ, 644, 551

- With modeling, spectroscopy allows us to detect life on other worlds that are too far away for us to travel to directly
- Care will be needed to weed out false positives where the detection of O_2 and O_3 is not a sign of life
- Comprehensive modeling of diverse data sets is key
- **UV, visible, and IR wavelengths all carry important information**

Some relevant features and what they tell us

Spectroscopic feature	σ (cm^{-1})	R = λ/Δλ	λ	Ref.	Importance[a]
O_3	31,000	16	320	1	Source is O_2; UV shield
Rayleigh scattering	N/A	5	< 500	2	Protective atmosphere
O_3	17,125	5	580	1,2	
O_2	14,515	54	690	1	Plants emit; animals inhale
H_2O	13,815	37	720	1	Needed for life
CH_4	13,780	57	730	1	Can have biological origin
Cloud/surface reflection	N/A	8	750	2	Rotation indicator
O_2	13,105	69	760	1,2	
Land plant reflection	N/A	8	770	2	Vegetated land area
CH_4	12,635	29	790	1	
H_2O	12,175	35	820	1	
CH_4	11,215	32	890	1	
H_2O	10,625	17	940	1,2	
CH_4	10,035	20	1,000	1	
CO_2	9,530	40	1,050	1	Important to surface temperature
H_2O	8,815	19	1,130	1	
CO_2	8,240	34	1,210	1	
O_2	7,895	72	1,270	1	
H_2O	7,110	10	1,410	1	
CO_2	6,295	11	1,590	1	
CH_4	5,900	10	1,690	1	
H_2O	5,330	11	1,880	1	
CO_2	4,930	16	2,030	1	
CH_4	4,305	8	2,320	1	
H_2O	1,428	10	7,000	1	
CH_4	1,306	13	7,650	1	
CH_4	1,253	6	7,980	1	
Cont.	1,154	8	8,670	1	
CO_2	1,074	19	9,310	1	
O_3	1,036	17	9,650	1	
CO_2	960	16	10,420	1	
Cont.	895	5	11,170	1	
CO_2	668	4	14,960	1	
H_2O	488	3	20,490	1	
H_2O	350	4	28,570	1	
H_2O	250	2	40,000	1	

[a]For each feature, we state its importance only the first time that it is mentioned.

[1]Des Marais et al. 2002, "Remote Sensing of Planetary Properties and Biosignatures on Extrasolar Terrestrial Planets.." Astrobiology 2 (2): 153–81. doi:10.1089/15311070260192246.

[2]Postman, M. et al. 2009, "Advanced Technology Large-Aperture Space Telescope (ATLAST): Characterizing Habitable Worlds." arXiv.org.

NASA Technology Readiness Levels

TRL

1. **Basic principles observed and reported:** Transition from scientific research to applied research. Essential characteristics and behaviors of systems and architectures. Descriptive tools are mathematical formulations or algorithms.

2. **Technology concept and/or application formulated:** Applied research. Theory and scientific principles are focused on specific application area to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.

3. **Analytical and experimental critical function and/or characteristic proof-of- concept:** Proof of concept validation. Active Research and Development (R&D) is initiated with analytical and laboratory studies. Demonstration of technical feasibility using breadboard or brassboard implementations that are exercised with representative data.

4. **Component/subsystem validation in laboratory environment:** Standalone prototyping implementation and test. Integration of technology elements. Experiments with full-scale problems or data sets.

5. **System/subsystem/component validation in relevant environment:** Thorough testing of prototyping in representative environment. Basic technology elements integrated with reasonably realistic supporting elements. Prototyping implementations conform to target environment and interfaces.

6. **System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space):** Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application.

7. **System prototyping demonstration in an operational environment (ground or space):** System prototyping demonstration in operational environment. System is at or near scale of the operational system, with most functions available for demonstration and test. Well integrated with collateral and ancillary systems. Limited documentation available.

8. **Actual system completed and "mission qualified" through test and demonstration in an operational environment (ground or space):** End of system development. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. Verification and Validation (V&V) completed.

9. **Actual system "mission proven" through successful mission operations (ground or space):** Fully integrated with operational hardware/software systems. Actual system has been thoroughly demonstrated and tested in its operational environment. All documentation completed. Successful operational experience. Sustaining engineering support in place.